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An assessment of groundwater recharge estimation techniques for sustainable resource management

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ABSTRACT

Groundwater resources are limited and they are declining in quality and quantity due to contamination and climate change impacts. Under the environment of the increasing water demand for domestic, agricultural, and industrial uses and dwindling resources, the management of groundwater resources is a challenging task worldwide. Precise evaluation of groundwater recharge is vital for its sustainable management and efficient use for various sectors of the economy. An overview of different groundwater recharge estimation techniques is presented in this paper. The techniques covered in this study include numerical approach, tracer method, hydrologic budget method, and multiple methods. The norms of recharge estimation through rainfall, canal seepage, and field percolation are also covered in this study. The literature analysis revealed that the tracer techniques are extensively used in water-scarce areas for estimating groundwater recharge. And the use of watertable fluctuations is a valuable means for shaping the size of both long and short-term alterations in recharge. The analysis also revealed that groundwater recharge can be estimated by using the numerical models. Because each approach is associated with some limitations, the use of multiple approaches was recommended to estimate the groundwater recharge. In many cases, diverse approaches balance every other and aid improve the conceptual model of recharge processes. This literature analysis provides the basis for the selection of an appropriate recharge estimation technique under a specific set of conditions.

1. Background

Groundwater resources are limited and they are declining in quality and quantity due to contamination and climate change impacts (Kalhor et al., 2019; Cheo et al., 2017; Singh, 2018a,b, 2014a). Under the environment of the increasing water demand for domestic, agricultural, and industrial uses and dwindling resources, the management of groundwater resources is a challenging task worldwide (Varua et al., 2018, Singh, 2014b,c). The problem has aggravated more in the recent time thanks to the rise in population and dwindling resource base caused by contamination and global change (Adhikari and Nejadhashemi, 2016; Singh, 2019a,b,c; 2018c). It has resulted in a rapid decline in surface water and groundwater reservoirs, deforestation, and desertification. Limited surface water availability is governed by spatial and stochastic phenomena of rainfall associated with structural measures in the river system (Adhikari et al., 2017; Gaaloul, 2014). Surface water sharing treaties between neighboring countries have put an additional constraint on its availability. Therefore, groundwater is very convenient to extract from the users perspective. But many regions experiencing waterlogging (FAO, 2016) by rising poor quality groundwater and limited fresh quality groundwater may be available at a deeper depth, which is expensive for exploration by the common user (Singh, 2015).

Therefore, it is imperative to increase the fresh groundwater potential for sustainable resource conservation. In this process, groundwater recharge plays a key role in water balance studies in these regions where potential evapotranspiration equals or surpasses average precipitation. Therefore, an accurate estimation of groundwater recharge is essential for efficient and sustainable groundwater management because water resources are critical to economic development in these areas (Leketa et al., 2019; Singh, 2011; 2012a; de Vries and Simmers, 2002). However, accurate recharge estimation is difficult in these areas

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(Kinzelbach et al., 2002; Sekhar et al., 2004). Various direct and indirect methods and sophisticated models have been used for the estimation of groundwater recharge since its direct measurement is nearly impossible. Researchers used various approaches for estimating the recharge (Lee et al., 2008; Rushton et al., 2006; Healy and Cook, 2002). The quantum of information needed for recharge estimation depends on the convolution of the method used. For instance, a number of methods involve the development of complex mathematical models while others require extensive fieldwork (Finch, 1998; Gogolev, 2002). Usually, the key methods for groundwater recharge estimation are numerical models, hydrological budgets, watertable fluctuations, and tracer techniques.

This study presents an overview of different techniques used for the estimation of groundwater recharge. Norms for the determination of different recharge components are also presented in this paper.

2. Numerical approach

Groundwater recharge can be estimated by using the numerical models (Wanke et al., 2008). The calibration process can be used for obtaining the recharge flux that is needed to match target heads (Said et al., 2005; Cherkauer, 2004). It is imperative to note that these models do not produce distinctive results for hydraulic heads for the reason that the results depend on how fit the boundary conditions and aquifer formation are described and assumptions were taken. Besides, developing numerical models is expensive, requires modeling ability, time-consuming, and requires widespread historical data. Many researchers have used numerical methods to solve the Richards equation and thus construct soil hydrological models for soil moisture simulation (Ross, 1990; Fayer, 2000). In a plain region, soil moisture progression in the vertical direction plays a central role and thus, a 1-D model should be enough. Such a model was developed by Chen and Hu (2004) to investigate the groundwater influence on soil moisture and surface evaporation (Chen et al., 2008).

Two unsaturated zone models, i.e., Richards equation and water balance-based, were used by Gogolev (2002)) for estimating groundwater recharge. While Ragab et al. (1997) applied a simple soil model for the accurate estimation of groundwater recharge. Similarly, Finch (1998) used a simple water balance model for estimating direct groundwater recharge. Monte Carlo Technique for recharge estimation was used by Beseki and MacConchie (1999). These models are good for estimating groundwater recharge. But, they need many field data such as rainfall, soil water content, potential evapotranspiration etc and include many model parameters which possession is a lot difficult and takes plenty of time, eventually limiting their real field applications. A conceptual rainfall-runoff model SMAR was used to overcome the aforesaid limitations. The SMAR estimates recharge using only groundwater level, rainfall, and evaporation. This model, however, cannot be used directly for an aquifer where horizontal groundwater flow is prominent. For this reason, a horizontal flow component was added to this model (Fazal et al., 2005).

Ketchum et al. (2000) and Avery et al. (1999) reported that recharge is estimated by multiplying the specific yield of the aquifer material with the amount of water level fluctuations in wells in the majority of previous studies. Yeh et al. (2007) and Louie et al. (2000) described the processes of groundwater recharge and fluxes of the water balance concept. Application of soil moisture budget and simulation models are currently considered as typical techniques for the estimation of regional groundwater recharge (Zhang et al., 1999; Chen et al., 2005). Diverse approaches including the boundary element, the finite element, and the finite difference method have been extensively used by the scholars for solving the groundwater flow equations, among which TOUGH2 (Pruess et al., 1999), MODFLOW (Chiang and Kinzelbach, 1998), and ROCKFLOW (Kohlmeier et al., 2007) are the most often used for simulating groundwater flow. The soil moisture budget method, which accounts for climatic conditions and soil properties, is used to approximate the evapotranspiration, runoff, infiltration, and recharge. The amount of recharge by rainfall infiltration determines the sustainability of a groundwater system (Lee et al., 2008).

A correct appraisal of water equilibrium at the regional level is of paramount substance in the environment of an overall rise in agricultural, urban, and industrial water demand. This equilibrium upshots from the interface of soil, climate, geology, and plants (de Vries and Simmers, 2002). Its appraisal is intricate particularly in dry regions because groundwater recharges and stream discharge fluxes are weak and variable (Scanlon et al., 2006). Appraising groundwater recharge as the residual of soil water balance equation is a common way of modeling watershed hydrology (Collins and Bras, 2007). Anuraga et al. (2006) presented a simple method that integrates the 1-D agro-hydrological model SWAP with the data available from government agencies and GIS to assess the effect of land use and soil on groundwater budgets at the sub-watershed scale.

There are several reviews on groundwater recharge estimation methods (Scanlon et al., 2002; Lerner et al., 1990). While these methods offer insights into the developments of groundwater recharge, they are unsuitable for normal recharge assessment (Rushton et al., 2006). Ragab et al. (1997) introduced alternative soil moisture balance models for recharge estimation. When there are consistent estimates of outflows from an aquifer due to pumping from boreholes or river flows, a groundwater balance possibly used to improve the recharge approximations (Kendy et al., 2003).

3. Tracer method

Groundwater recharge may be estimated by several conventional methods (Nimmo et al., 2005) but most methods require analysis of a large volume of hydrological data, which is scarce in several regions (Chand et al., 2004). Tracer techniques are broadly employed in dry areas for recharge approximation from irrigation and rainfall (Robertson and Cherry, 1989; Wood and Sanford, 1995; Sami and Hughes, 1996; Cook and Solomon, 1997). Common tracers include bromide (Jury et al., 1982; Hendrickx et al., 1993), ^{3}H (Rangarajan et al., 2005), and visible dyes (Flury et al., 1994; Forrer et al., 1999). A benefit of tracer techniques is that the requirements are generally for shorter-term and straightforwardly available data (Chand et al., 2004; Zimmermann et al., 1966; Dincer et al., 1974; Athavale et al., 1980). Generally, three types of tracer techniques, i.e., applied tracers, environmental tracers, and historical tracers are used for the determination of groundwater recharge (Edson, 1998).

Environmental tracers, i.e., chloride are applied physically on the ground surface in the course of the earth's environment (Phillips, 1994). With a perception of how they accrue and move across in the vadoze zone, they can be used for estimating normal recharge (Scanlon, 2000). Historical tracers are the result of human activities, i.e., nuclear testing and contaminant spills (Nativ et al., 1995). The recharge rates of more than past 50 years can be estimated by using these historical tracers (Lin and Wei, 2006; Cook et al., 1994; Allison and Hughes, 1983). Applied tracers typically are chosen chemicals that are available at low concentrations, injected at some depth or applied at the soil surface. Which is then transported downward by unsaturated-zone water. The average transport velocity which indicates a recharge rate is expressed by the depth of the tracer front.

Ayers (1981) reported that chloride ion, which is concentrated by the processes of evapotranspiration, can be used as a tracer for estimating groundwater recharge estimation of fresh-water lenses. Vacher and Ayers (1980) reported that this method is effective in recharge estimation regardless of the fact whether the recharge is diffused or focused. With some assumptions and conditions, the chloride mass balance method offers rational estimates of groundwater recharge in semiarid areas which are very similar to those acquired by physically based methods (Wood and Sanford, 1995). The overall disadvantages

associated with tracer techniques comprise, the extra cost to use tracers, the time lapse between submission and sampling, and likely complexity in getting the ideal site to sample (Wang et al., 2008b). In addition, the measurement through this method may result in an over or under-estimation of recharge because it does not measure recharge directly (Lerner et al., 1990).

4. Hydrologic budget method

Analysis of watertable fluctuations is a valuable means for shaping the size of both long and short-term alterations in recharge (Avery et al., 1999; Ketchum et al., 2000). Groundwater Estimation Committee (India) has also recommended this method for estimation of groundwater recharge. However, use of this method is restricted in regions, where watertable scrutiny is frequently performed (Sharda et al., 2006). Furthermore, using a distinct value of specific yield bounds the utility of this method.

Healy and Cook (2002) estimated groundwater recharge by using watertable fluctuation method as:

$$\text{Rech} = S_y\ (\Delta h/\Delta t) \quad (1)$$

where Rech is recharge, S_y is specific yield, t is time, and h is watertable depth. However, this method is primarily suitable over a short period of time such as up to a small number of days (Yasuda et al., 2013; Healy and Cook, 2002). Yasuda et al. (2013) have undertaken a study to simplify groundwater recharge alongside the interface between the low groundwater and plant ecosystem at a location in the Loess Plateau of China.

The hydrological budget method is widely used by hydrologists for estimating groundwater recharge (Ahmed and Umar 2008; Marechal et al., 2006). This method accounts for all inflow and outflow constituents, in addition to storage changes in the saturated and unsaturated zones. The method uses specific yield for the calculation of the drained water quantity from inundated storage. However, assigning a representative value of specific yield leads to over/under estimation of groundwater recharge (Sophocleous, 1985). The common hydrologic account of a region can be given as:

$$\Delta S = (I + R_c + R_p + R) + (Q_{in} - Q_{out}) - (RO + ET_c + Q_w) \quad (2)$$

where ΔS is the net groundwater recharge (change in saturated groundwater storage); I and R are the irrigation and rainfall, respectively; R_c is the groundwater recharge due to canal seepage; R_p is the groundwater recharge due to field percolation; Q_{in} and Q_{out} are lateral water fluxes into and out of the command area; RO is surface water runoff; ET_c represents water losses due to crop evapotranspiration; and Q_w is groundwater withdrawal through tubewells.

By and large, using this method for estimating groundwater recharge is inexact thanks to complexities in establishing some parameters for example runoff, groundwater baseflow, evapotranspiration, and an interception, and the use of a distinct value for specific yield (Manghi et al., 2009). Saraf and Choudury (1998), Jackson (2003), and Ghayoumian et al. (2006) advocated the use of geospatial techniques such as GIS for recharge estimation through the modeling of groundwater resources.

5. Multiple methods

The groundwater recharge is computed by various methods and techniques such as saturated and unsaturated-zone techniques etc. However, since each approach is associated with some limitations, the use of multiple approaches was recommended to estimate the groundwater recharge (Risser et al., 2009; Healy and Cook, 2002). In many cases, diverse approaches balance every other and aid improve the conceptual model of recharge processes. The direct measurement of groundwater recharge is virtually impractical, thus scholars usually construct the unsurpassed estimates by the use of techniques that are relatively straightforward in their application and need only commonly available hydrologic data. It was commonly recommended that groundwater recharge should be appraised by using the several methods and the results judged against (Nimmo et al., 2003). This is a sensible technique, nevertheless, quality data generally are not accessible to use several methods. Risser et al. (2009) summarized a study which evaluates the results of groundwater recharge from four methods. The development and application of a simple groundwater recharge model was presented by Singh (2012b). The presented model is simple and it entails inputs that are easily obtainable or accessible. The model was used to evaluate the groundwater recharge of a canal command in an irrigated area of India. Reviews on groundwater recharge estimation are available by Lerner et al. (1990), Simmers (1997), Sanford (2002), and Scanlon et al. (2002). The key assessment norm for selecting the right technique is the likely correlation between indirect and direct recharges. If direct recharge is the main process, water balance models, the chloride mass balance method, or numerical analysis of vertical moisture flux can be used.

6. Recharge estimation norms

6.1. Recharge from rainfall

Statistical studies carried out by researchers worldwide i.e., Taylor et al. (1933) and Wilsdon and Sarathy (1931) indicated that on an average, about one-third of the water added to the surface of the soil during the year percolates down to the watertable. However, Singh (1973) has used the following equation for the calculation of recharge through rainfall:

$$Q_r = \{C_r - (R_o + E_t)\} \times A_c \quad (3)$$

where Q_r is the volume of the water available for recharge, C_r is the contributing part of the rain, R_o is the direct runoff, E_t is evapotranspiration, and A_c is the area of the catchment.

The contribution of rainfall in the groundwater recharge is variable significantly with the type of soil and geological conditions (Rangarajan and Athavale, 2000). For example, for granite the annual recharge (Rech, mm) is related to the annual rainfall (RF, mm) as: {Rech = 0.172 (RF)-44}, while for the alluvium soil the relationship would be given as: {Rech = 0.147 (RF)-6}. Similarly, Chandra and Saxena (1975) provided the following relationships between annual recharge and annual rainfall:

$$\text{Rech} = 3.984\ (\text{RF-}40.4)^{0.5} \quad (4)$$

Researchers such as Singh and Kumar (1994), Singh et al. (2010), and Singh (2013) estimated that 20% of the total rainfall contributes to the recharge of groundwater, while Gupta (1983) reported a recharge of 20–25% for the alluvial sandy areas. However, for the areas with large clay content, rainfall recharge is suggested be 15–20% of the annual rainfall.

6.2. Recharge from canal seepage

Groundwater recharge through canal seepage has been estimated for different sets of specific conditions by many researchers, i.e., Wolde-Kirkos and Chawla (1994), Sharma and Chawla (1975), Singh et al. (2012), Subramanya et al. (1973), Morel-Seytoux (1964), Garg and Chawla (1970), and Harr (1962). The aforementioned studies provided an accurate mathematical solution to unconfined steady-state seepage from the canal networks in the homogeneous porous medium. They reported a seepage loss of about 45% of the water supplied to the head of the canal by the time the water reaches the field. According to the Bureau of Indian Standards (1980), the seepage loss from unlined canals normally ranges between 0.3 and 7.0 m^3/s per million m^2 of wetted

surface. An assessment of canals by Wachyan and Rushton (1987) showed that even with the utmost care the canal lining does not stay faultless. Tahir et al. (1996) modeled the transmission losses series as an autoregressive-integrated-moving average (ARIMA) process. The researchers such as Tyagi (1983), Singh and Kumar (1994), and Singh et al. (2012) estimated the canal seepage as:

$$R_c = WP_c \times N_d \times L_c \times SF \times 86400 \quad (5)$$

where N_d is the number of running days (day), L_c is the length of specific canal (m), SF is the seepage factor, WP_c is the wetted perimeter of the canal (m), and R_c is the groundwater recharge due to canal seepage (m^3). The rate of SF was suggested at 0.62–0.75 and 2.5–3.0 m^3/sec/Mm^2 of the wetted area for lined and unlined canals, respectively (Irrigation Department, 2016).

The above method provides an approximate estimation of the canal seepage. For precise estimation using above method, it is essential to divide the entire length of canal to different sections depending on cross-sections as it reduces from head-reach to tail-reach. Wetted perimeter is also dynamic depending on full- or partial-supply of irrigation water at the head regulator. It has been observed that some of the lined canals act as unlined system depending on life and quality of construction of the structure. Moreover, due to siltation in canal bed, seepage from the unlined canals reduced substantially. Due to the rodent problem in the embankment of the unlined canal, almost entire irrigation water is available in the fields on both sides of the canal. Therefore, more research is required to establish the seepage factor (SF) according to canal embankment material, the life of the structure, and human/animal interventions.

6.3. Recharge from field percolation

The Groundwater Estimation Committee (India) suggested the guidelines for the estimation of recharge from irrigated fields (Singh et al., 2010). The diverse proportion of deep percolation in cropped areas taken was based on the studies undertaken in comparable areas for diverse crops. The groundwater recharge through the cropped field was estimated as:

$$R_p = D \times A \times D_f \quad (6)$$

where D is the irrigation water depth given to the field (m), A is the area under specific crop (m^2), D_f is the portion of applied water added as groundwater recharge, and R_p is the groundwater recharge due to field percolation (m^3). Therefore, D_f is dynamic as it depends on crop and soil moisture status on the day of irrigation.

A major portion of the field percolation losses comes from rice field (Tuong and Bhuiyan, 1999) as about 59% of the total water applied, lost as deep percolation, while it is only 5.6% for wheat and 31.2% for sorghum crop. The water balance of paddy fields has been analyzed by Kampen (1970) using both numerical and analog models. Smith (1991) introduced paddy into the computations of the CROPWAT program, adopting a specific procedure.

7. Summary and conclusions

There are diverse indirect and direct approaches and advanced models have been used for groundwater recharge estimation since its direct measurement is nearly impossible. Tracer techniques are extensively used in water-scarce areas for estimating groundwater recharge from irrigation and rainfall. However, it requires more cost in applying and the time required between applications and sampling. Moreover, the measurement through this method may result in an over or underestimation of recharge because it does not measure recharge directly. The use of watertable fluctuations is a valuable means for shaping the size of both long and short-term alterations in recharge. However, use of this method is restricted in regions, where watertable scrutiny is frequently performed. Furthermore, using a distinct value of specific yield bounds the utility of this method. Groundwater recharge can be estimated by using the numerical models. The calibration process can be used for obtaining the recharge flux that is needed to match target heads. But, these models do not produce distinctive results for hydraulic heads for the reason that the results depend on how fit the boundary conditions and aquifer formation are described and assumptions were taken. In addition, these models require extensive historical data and modeling expertise. The hydrological budget method is widely used by hydrologists for estimating groundwater recharge. However, assigning a representative value of specific yield leads to over-/underestimation of groundwater recharge. Because each approach is associated with some limitations, the use of multiple approaches was recommended to estimate the groundwater recharge. In many cases, diverse approaches balance every other and aid improve the conceptual model of recharge processes.

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